

Zurich University ZU-TH 27/96

BARYONIC DARK MATTER ¹

F. De Paolis^{2,3}, G. Ingrosso², Ph. Jetzer³ and M. Roncadelli⁴

² Dipartimento di Fisica, Università di Lecce, CP 193, 73100 Lecce, Italy
and INFN, Sezione di Lecce, CP 193, 73100 Lecce, Italy

³ Paul Scherrer Institute, Laboratory for Astrophysics,
CH-5232 Villigen PSI,
and Institute of Theoretical Physics, University of Zurich,
Winterthurerstrasse 190, CH-8057 Zurich, Switzerland

⁴ INFN, Sezione di Pavia, Via Bassi 6, I-27100, Pavia

Abstract

Reasons supporting the idea that most of the dark matter in galaxies and clusters of galaxies is baryonic are discussed. Moreover it is argued that most of the dark matter in galactic halos should be in the form of MACHOs and cold molecular clouds.

¹Talk presented by F. De Paolis at the workshop on “Dark and visible matter in galaxies and cosmological implications” (Sesto Pusteria, July 1996)

1 Introduction

One of the most important problems in modern astrophysics concerns the nature of the dark matter that pervades the Universe. Probably, more than 90% of the matter in our Universe is dark. Evidence for the existence of dark matter comes from the observation that the dynamics of many astronomical systems, such as galaxies and clusters of galaxies, cannot be explained by the visible matter alone.

The most impressive evidence for dark matter is provided by measurements of the rotational velocities of stars and gas clouds in spiral galaxies. The dependence of the rotational speed from the galactocentric distance is, in fact, a measure of the total mass density profile $\rho(r)$. An important feature of many spirals is that their rotation curves, after an initial rise, remain almost constant with increasing galactocentric distance (Rubin, Ford & Thonnard, 1980). This fact yields convincing evidence that the dynamical mass of spirals increases much more rapidly than the visible matter with increasing radial distance from the galactic centre (see e.g. Persic, Salucci & Stel 1996). Observations as well as theoretical arguments (linked to the stability of disks) suggest that the dark matter is distributed in the form of spherical (or slightly oblate) halos around galactic disks.

The presence of dark matter in elliptical galaxies is less evident as compared with the case of spirals, mainly due to the lack of neutral gas observable in the radio band (Sarazin 1987, Kent 1990). Since the motion of stars in ellipticals is irregular and any rotation appears to be small, the Doppler-shift technique cannot be applied in the same way as for spirals. However, certain ellipticals are surrounded by a hot, ionized gas emitting in the X-ray band (due to Bremsstrahlung emission) which can be used to determine the galaxy gravitational potential. Assuming that the gas is in hydrostatic equilibrium, the virial theorem relates the kinetic energy of the gas to its gravitational binding energy. It is then possible to show that, for the gas to remain confined within the galaxy, there must be much more mass than just the visible matter (Fabricant & Gorenstein 1983, Fabricant, Lecar & Gorenstein 1980, De Paolis, Ingrosso & Strafella 1995).

As far as clusters of galaxies are concerned, very convincing evidence for dark matter comes from investigations of the dynamical properties of galaxies, the gravitational lensing of distant background objects and the X-ray data from the Bremsstrahlung emission of fast moving electrons in the

hot intergalactic plasma.

Candidates for dark matter can be divided into two categories: those motivated by particle physics and those suggested by astronomy. The first category includes weakly interacting massive particles (WIMPs): massive neutrinos, axions and particles predicted by supersymmetric theories (SUSY). Among the particles candidates the neutrino is the only one known to exist. Many experiments have searched for neutrino masses but, so far, strong enough limits have not been put. Neutrinos have been produced during the Big Bang and contribute to the density of the Universe with a fraction $\Omega \simeq (n_\nu/n_\gamma)(m_\nu/25 \text{ eV})$, where n_ν and n_γ are the number density of neutrinos and photons, respectively. Since most of the Big Bang models predict that the relic abundance of neutrinos is comparable with that of photons, one obtains that neutrinos with a mass $m_\nu \geq 25 \text{ eV}$ can close the Universe. Candidates motivated by astronomy include brown dwarfs, white dwarfs, neutron stars, black holes and cold clouds.

In the following sections we discuss several reasons that lead us to believe that most of the dark matter in galaxies and clusters of galaxies should be baryonic. Obviously, galaxy formation remains an open problem in this view, and the only explanation to date requires non-baryonic dark matter. Still, the point we want to make is that many properties of galaxies and clusters of galaxies are naturally accounted for by baryonic dark matter alone.

2 MACHOs and molecular clouds

From the standard Big Bang nucleosynthesis model (Copi, Schramm & Turner 1995) one infers that $0.01 < \Omega_B < 0.1$ (Particle Data Group 1996). Since for the amount of luminous baryons one finds $\Omega_{\text{lum}} \ll \Omega_B$, it follows that an important fraction of baryons are dark and they may well make up the entire dark matter in galactic halos. The halo dark matter of our galaxy cannot be in the form of hot diffuse gas otherwise there would be a large X-ray flux, for which stringent upper limits are available. The abundance of neutral hydrogen gas is inferred from the 21-cm measurements, which show that its contribution is small. Another possibility is that the hydrogen gas is in molecular form clumped into cold clouds. Baryons could otherwise have been processed in stellar remnants. A natural option is provided by brown dwarfs with mass below $\sim 0.1 M_\odot$, which would be too light to ignite the

hydrogen burning reactions. In principle, also M-dwarfs and white dwarfs could be conceived as dark matter candidates. However, a deeper analysis shows that the M-dwarf option is problematic. Indeed, optical imaging of high-latitude fields taken with the Wide Field Camera of the Hubble Space Telescope indicates that less than a few percents of the galactic halo can be in this form (Bahcall et al. 1994, Hu et al. 1994). A scenario with white dwarfs as a major constituent of the galactic halo has been explored (see e.g. Adams and Laughlin 1996) but it requires a rather *ad hoc* initial mass function peaked somewhere around $2-6 M_{\odot}$.² On the other hand, a substantial component of neutron stars and black holes with mass $\geq 1 M_{\odot}$ is excluded due to the overproduction of heavy elements.

Thus, brown dwarfs and cold molecular clouds are probably the best candidates for dark matter in galaxies. Paczyński (1986) proposed the idea of using gravitational micro-lensing to detect massive dark object in our galaxy by monitoring the brightness of stars in the Magellanic Clouds. The light from a distant star should in fact be deflected by the gravitational field of a massive object close to the line of sight from the Earth to the star. For typical masses and distances of halo dark objects (i.e. for deflection angles $\sim 10^{-6}$ arcsec), the star will appear brighter than in the absence of a deflector.

Recent observations of microlensing events (Alcock et al. 1993, Aubourg

² Moreover, a halo primarily made of white dwarfs would have left too much diffuse hot gas at temperature $\sim 2 \times 10^6$ K emitting in the X-ray band. Here we note that Adams and Laughlin (1996) do not take into account in their calculations the different evolution of low metallicity stars (that would produce the halo white dwarfs) with respect to stars with solar metallicity. White dwarfs in the galactic disk have average mass $\sim 0.7 M_{\odot}$, whereas white dwarfs originating from low metallicity stars are expected to have larger masses. Roughly speaking, the white dwarf mass is correlated to the mass of the star helium core, i.e. the mass inside the region where the radiative gradient ∇_{rad} is larger than the adiabatic gradient ∇_{ad} . While ∇_{ad} is approximately constant, ∇_{rad} strongly depends on the metallicity; this would generate more massive *He* cores with decreasing star metallicity. This behaviour is also confirmed by numerical simulations (Lattanzio 1991) of the evolution of the stellar parameters from the Main Sequence to the first thermal pulse. Another problem with the analysis of Adams & Laughlin is the choice of $\sim 8-10 M_{\odot}$ as the mass above which a star becomes a supernova (SNII); due to the low metallicity of primordial halo stars, however, also stars with masses well below $8 M_{\odot}$ will end their life as SNII, thus producing neutron stars (Jura 1986). So, we are then left with the only possibility that MACHOs (Massive Astrophysical Compact Halo Objects) are brown dwarfs with mass $\leq 0.1 M_{\odot}$.

et al. 1993) towards the Large Magellanic Clouds (LMC) suggest that MACHOs provide a substantial amount of the halo dark matter. Assuming a standard spherical halo model (in which the MACHO velocity distribution function is taken to be Boltzmannian), it has been found that the 8 microlensing events found so far (Alcock et al. 1996) imply a halo MACHO fraction as high as 50% and an average mass of $0.27 M_{\odot}$ (Jetzer 1996). However, we note that the statistics of these events is at present too low to infer any definite conclusion since both the halo fraction in the form of MACHOs and their average mass strongly depend on the assumed model for the visible and dark matter components of the galaxy (see De Paolis, Ingrosso & Jetzer 1996).

Several authors have studied the problem of determining the number of the expected microlensing events or, equivalently, the optical depth to microlensing by considering different models for the mass distribution, both luminous and dark in the galaxy (Kerins 1995, Kan-ya, Nischi & Nakamura, 1995, Evans & Jijina 1994, Evans 1994). Recent upgraded self-consistent galactic models which include anisotropies in phase space for the MACHO distribution and a more realistic model for the distribution of the galactic luminous matter (De Paolis, Ingrosso & Jetzer 1996) show that the values for the microlensing rate can decrease with respect to the standard values, thereby making brown dwarfs a plausible candidate for MACHOs.

The problem arises of how MACHOs formed and in what form the remaining fraction of the galactic dark matter is. A scenario in which dark clusters of MACHOs and cold molecular clouds naturally form in the halo at large galactocentric distances has been recently proposed (De Paolis et al. 1995a-c)³ and several methods to test this model have been proposed (De Paolis et al. 1995d). Basically, here the dynamics of the formation of dark clusters is similar to that of stellar globular clusters, the only difference being the larger galactocentric distance of dark clusters and consequently the lower incoming UV flux (from a central source). This fact implies that molecular hydrogen in dark clusters is not dissociated so that the Jeans mass can naturally reach values as low as $\sim 10^{-2} - 10^{-1} M_{\odot}$, leading to the formation of MACHOs. It is important to note that also molecular clouds should form in dark clusters, since the process leading to MACHO formation does not have a 100% efficiency and the gas cannot be expelled due to the absence of

³Similar ideas have been put forward by Gerhard & Silk (1995).

strong stellar winds.

3 Dark matter at the centre of galaxies

Recent observations of the central flatness of the velocity profiles of dark halos seem to suggest that dark matter in galaxies is baryonic. In fact, several computer simulations of the large scale structure of the Universe with non-baryonic dark matter (and in particular with *cold* vvdark matter) with a sufficiently high resolution to resolve the internal structure of the galactic halos, seem to indicate that the density profiles should have central cusps. These cusps are incompatible with the isothermal density profiles

$$\rho(r) = \frac{\rho(0)}{1 + (r/a)^2} , \quad (1)$$

where a is the dark matter core radius. While this profile becomes approximately constant at $r \ll a$ and has a finite central density $\rho(0)$, numerical simulations indicate a density distribution that diverges like r^{-1} (Burkert 1995). The existence of a central density cusp in normal galaxies is difficult to demonstrate since the internal regions are gravitationally dominated by the visible component. The distribution of dark matter, in fact, strongly depends on both the assumed mass/luminosity ratio (M/L) for the disk and for the central spheroidal component. The situation is different in dwarf galaxies which have recently been studied using high resolution methods. Dwarf spiral galaxies provide excellent probes for the internal structure of dark halos since these galaxies are completely dominated by dark matter on scales larger than a kiloparsec (Carignan & Beaulieu 1989, Lake, Schommer & van Gorkom 1990, Jobin & Carignan 1990, Carignan & Freeman 1988). One can, therefore, use these galaxies to investigate the inner structure of dark halos with very little ambiguity about the contribution from the luminous matter and the resulting uncertainties in the disk M/L ratio. Only about a dozen rotation curves of dwarf galaxies have been measured, but a trend clearly emerges: the rotational velocities rise over most of the observed region, which spans several times the optical scale lengths and nevertheless lies within the core radius of the mass distribution. Rotation curves of dwarf galaxies do not admit singular density profiles at the galactic centre and their profiles are in good agreement (see Flores & Primack 1988, Moore 1994) with

Eq. (1). The shape of the central cores of dark matter can be explained with the model we have briefly discussed in Sect. 2 in which the dark matter in galaxies is constituted by dark clusters (DC) of MACHOs and cold molecular clouds that should form mainly at distances larger than $R_{\text{crit}} \sim 5 - 10$ kpc. Baryonic dark matter inside R_{crit} should derive from DCs broken during the galactic evolution (due to encounters among DCs or passages of them through the disk). This gas should form stars or remain in gaseous form, but the dark matter can never have a central density cusp since the gas has to thermalize and then its density profile is still dictated by eq. (1).

4 Galactic evolution along the Hubble sequence

It has been recently pointed out (Pfenniger, Combes & Martinet 1994) that spiral galaxies evolve along the Hubble sequence from S_d to S_a in billions of years. During this evolution the dimensions of both galactic nuclei and disks increase while the M/L ratio should decrease. This fact suggests that dark matter gradually transforms into visible matter, that is in stars. Of course, this is possible only if the dark matter is baryonic and in particular if it is in gaseous form. In the scenario of Pfenniger, Combes and Martinet (1994) the dark matter, in the form of self-gravitating H_2 clouds, is in the galactic disk. The clouds have a fractal structure that ranges upwards over 4 to 6 orders of magnitude in scale. The elementary cloudlets have low temperature ~ 3 K, typical number density $\sim 10^9 \text{ cm}^{-3}$, size $\sim 5 \times 10^{-6}$ pc and mass $\sim 10^{-3} M_\odot$. On the contrary, in the framework of our model (De Paolis et al. 1995a-d e 1996a), the galactic dark matter is composed of MACHOs and molecular clouds located in the galactic halo.

5 Rotation curve shapes

Initial studies have indicated that rotation curves of spiral galaxies are generally flat. This means that the galactic halo must produce practically the entire rotational velocity far out the optical radius, while in the internal regions the optical disk maximally contributes to the rotation curve. It seems that disk and halo combine together to produce a flat rotation curve. This synphony between disk and halo has been called the *disk-halo conspiracy* (van

Albada & Sancisi 1986, Sancisi & van Albada 1987). However, more recent observational results indicate that this *conspiracy* is not always true. For example, in some dwarf irregular galaxies the dark halo mass is considerably higher than the luminous disk mass inside the optical radius. Persic and Salucci (1988) developed a method to estimate the dark matter fraction inside R_{25} by using the shape of the rotation curves in the optical band. This study suggests that the fraction of the dark matter increases as the luminosity of spiral galaxies decreases. Then, in the internal regions of bright spirals the disk is the dominant component while the halo contributes significantly to the rotation curve only at large distances from the galactic centre. Vice versa, in low luminous galaxies, the dark halo seems to dominate at all scales. Based on these results one can predict that rotation curves in bright spirals should decrease at distances larger than the optical radius while in low luminous galaxies the rotation curve has to remain flat or increase beyond the optical radius. Combining the rotation curves obtained from HI observations for many spirals with the curves reported in the literature (Casertano & Van Gorkom 1991), the decrease of the rotational velocity beyond the optical radius in bright spirals has been identified. As predicted, the rotational velocities turn out to be flat or to increase in low luminous spiral galaxies. Moreover, a correlation between the maximum velocity and the slope of the rotation curve beyond the optical radius has been found. The dependence of the rotation curves on the luminous content of the spiral galaxies we are talking about can be explained if the dark matter in spirals is baryonic and in particular if halos formed before galactic disks (Ashman 1992, Persic & Salucci 1991), as it naturally happens in our model (De Paolis et al. 1995a-d).

6 Dark matter in clusters of galaxies

It is well known (see e.g. Blumenthal et al. 1984) that the ratio M/L increases from the luminous part of galaxies to clusters and superclusters of galaxies. This fact has generally induced astrophysicists to conclude that clusters and superclusters of galaxies have much more matter per unit luminous matter than individual galaxies, so that the critical density of the Universe ($\Omega = 1$) can be attained.

Recently, it has been shown (Bahcall, Lubin & Dorman 1995) that most of the dark matter in clusters and superclusters of galaxies should be clumped

in the halos around galaxies. Indeed, the ratio M/L in clusters does not significantly increase at scales larger than 100-200 kpc, typical of galactic halos. The total mass of the clusters can then be accounted for by the mass of the individual galaxies plus the hot gas mass (that represents less than $\sim 20\%$ of the total cluster mass). This fact suggests that Ω can be as low as ~ 0.2 , marginally consistent with the limits from the Big Bang nucleosynthesis (Sect. 2).

7 Conclusions

The wide-spread opinion in the scientific community that dark matter in galaxies and clusters of galaxies cannot be baryonic looks as an unwarranted conclusion. As we have discussed in the previous sections, there are many reasons to believe that dark matter in galaxies and clusters of galaxies is baryonic. The most likely dark matter candidates in galaxies are brown dwarfs and cold molecular clouds (Sect. 2).

MACHOs have been discovered by gravitational microlensing events towards stars in the LMC. It is unlikely that MACHOs are hydrogen-burning stars with masses in the range $0.1 - 0.3 M_{\odot}$ due to their emission in the infrared band (Hu et al. 1994). Also the possibility that MACHOs are white dwarfs with masses of $0.2 - 0.3 M_{\odot}$ gives rise to various problems, as discussed in section 2. We note that in the proposed model for the galactic dark matter it can be expected that a considerable number of MACHOs is in binary systems. This is especially true for MACHOs in the core of the dark clusters (see De Paolis et al. 1996b). This can obviously explain an increase up to a factor of 2 in the MACHO mean mass as measured by microlensing experiments towards stars in the LMC.

We have discussed many evidences for baryonic dark matter. These evidences arise from the shape of the dark matter density profiles towards the centre of dwarf galaxies, from the evolution of spiral galaxies along the Hubble sequence, and from the shape of rotation curves of spiral galaxies. On larger scales, another evidence supporting a baryonic scenario comes from the analysis of the M/L ratio of clusters of galaxies.

8 References

- Adams, F. C. & Laughlin, G. 1996, astro-ph/9602006
- Alcock, C. *et al.* 1993, *Nature*, 365, 621
- Alcock, C. *et al.* 1996, astro-ph 9606165
- Ashman, K. M. 1992, PASP, 104, 1109
- Aubourg, E. *et al.* 1993, *Nature*, 365, 623
- Bahcall, J., Flynn, C., Gould, A & Kirhakos, S. 1994, ApJ, 435, L51
- Bahcall, N. A., Lubin, L.M. & Dorman, V. 1995, ApJ, 447, L81
- Blumenthal, G. R., Faber, S. M., Primack, J. R. & Rees, M. J. 1984, *Nature*, 311, 517
- Burkert, A. 1995, ApJ 447, L25
- Carignan, C. & Beaulieu, S. 1989, ApJ 347, 760
- Carignan, C. & Freeman, K. C. 1988, ApJ 332, L33
- Casertano, S. & Van Gorkom, J. H. 1991, ApJ 101, 1231
- Copi, C. J., Schramm, D. N. & Turner, M. S. 1995, *Science*, 267, 192
- De Paolis, F., Ingrosso, G. & Jetzer, Ph. 1996, ApJ October 10, 1996 issue (in press)
- De Paolis, F., Ingrosso, G., Jetzer, Ph. & Roncadelli, M. 1995a, *Phys. Rev. Lett.*, 74, 14
- De Paolis, F., Ingrosso, G., Jetzer, Ph. & Roncadelli, M. 1995b, *Astron. & Astrophys.* 295, 567
- De Paolis, F., Ingrosso, G., Jetzer, Ph. & Roncadelli, M. 1995c, *Comm. Astrophys.*, 18, 87
- De Paolis, F., Ingrosso, G., Jetzer, Ph., Qadir, A. & Roncadelli, M. 1995d, *Astron. & Astrophys.* 299, 647
- De Paolis, F., Ingrosso, G., Jetzer, Ph. & Roncadelli, M. 1996a, *Int. J. Mod. Phys. D*, 5, 151
- De Paolis, F., Ingrosso, G., Jetzer, Ph. & Roncadelli, M. 1996b, in preparation
- De Paolis, F., Ingrosso, G. & Strafella, F. 1995, ApJ 438, 83
- Evans, N. W. & Jijina, J. 1994, MNRAS 267, L21
- Evans, N. W. 1994, MNRAS 267, 333
- Fabricant, D. & Gorenstein, P. 1983, ApJ 267, 535
- Fabricant, D., Lecar, M. & Gorenstein, P. 1980, ApJ 241, 552
- Flores, R. A. & Primack, J. R. 1988, ApJ 427, L1
- Gerhard, O. & Silk, J. 1995, astro-ph 9509149

- Hu, E. M., Huang, J. S., Gilmore, G. & Cowie, L. L. 1994, *Nature*, 371, 493
- Jetzer, Ph 1996, to appear in *Helv. Phys. Acta*
- Jobin, M. & Carignan, C. 1990, *Astron. J.*, 100, 648
- Jura, M. 1986, *ApJ* 301, 624
- Kan-ya, Y., Nischi, R. & Nakamura, T. 1995, astro-ph 9505130
- Kent, S. M. 1990, in *Evolution of the Universe*, ASP Conference Series Vol. 10, Ed. R. G. Kron, Brigham Young Univ. Printing Services, pag. 109
- Kerins, E. 1995, *MNRAS* in press (astro-ph 9406040)
- Lake, G., Schommer, R. A. & van Gorkom, J. H. 1990, *Astron. J.* 99, 547
- Lattanzio, J. C. 1991, *ApJS* 76, 215
- Moore, B. 1994, *Nature*, 370, 629
- Paczynski, B. 1986 *ApJ* 304, 1
- Particle Data Group 1996, *Phys. Rev.*, D54, 109
- Pfenniger, D., Combes, F. & Martinet, L. 1994, *Astron. & Astrophys.* 285, 79
- Persic, M. & Salucci, P. 1988, *MNRAS* 234, 131
- Persic, M. & Salucci, P. 1991, *MNRAS* 248, 325
- Persic, M., Salucci, P. & Stel, F. 1996, *MNRAS* 281, 27
- Rubin, V. C., Ford, W. K. & Thonnard, H. 1980, *ApJ* 238, 471
- Sancisi, R. & van Albada, T. S. 1987, *IAU Symp. 117, Dark matter in the Universe*, Eds. J. Kormendy, G. R. Knapp, Reidel Publishing Company, pag. 67
- Sarazin, C. L. 1987, in *Structure and Dynamics of Elliptical Galaxies*, IAU Symp. 127, Ed. P. T. de Zeeuw, Reidel, Dordrecht, pag. 179
- van Albada, T. S. & Sancisi, R. 1986, *Philos. Trans. Royal Soc. Lond. A*, 320, 447